

MECHANICAL ENERGY SYSTEMS FOR LOW GRADE WASTE HEAT RECOVERY

Contact:

Dr. Todd M. Bandhauer

Assistant Professor and Director, ITS-Lab

Colorado State University

tband@colostate.edu, 970-491-7357

www.theitslab.com



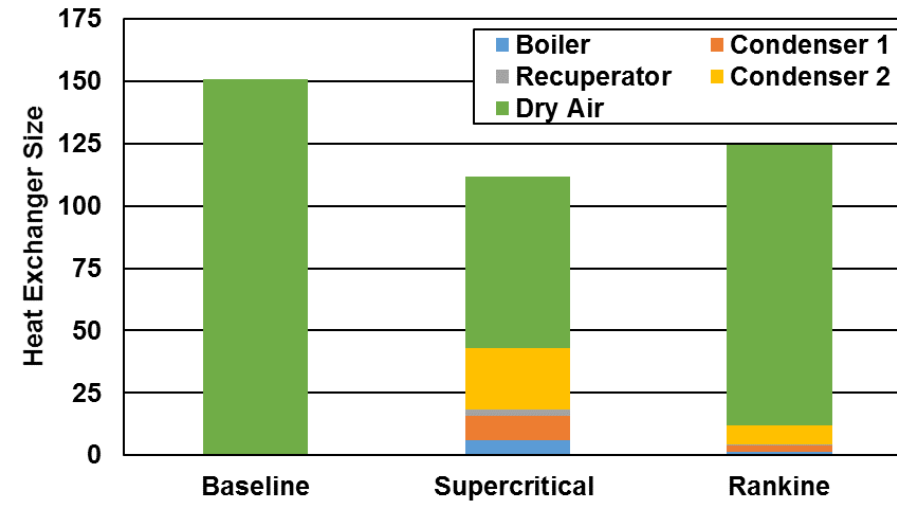
Colorado State University



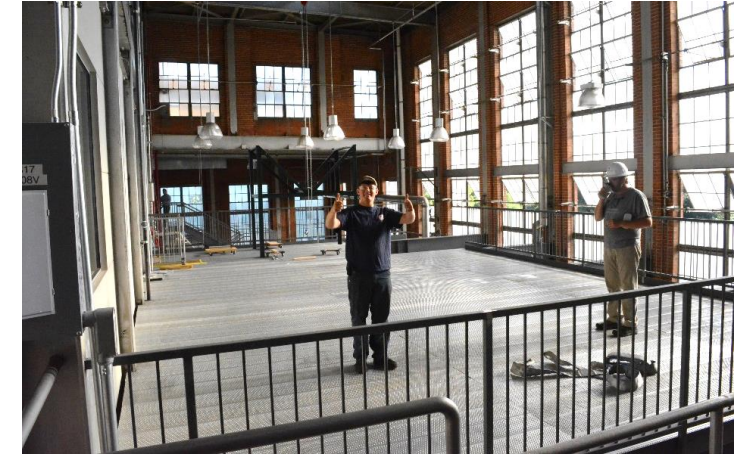
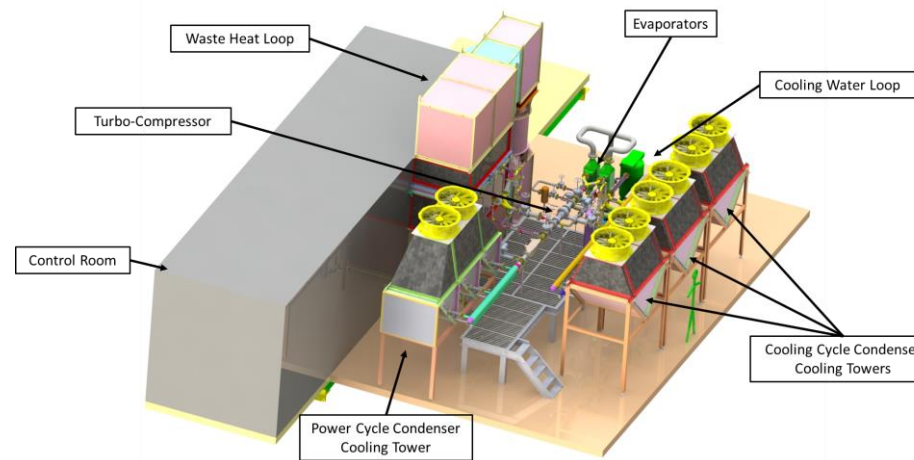
**INTERDISCIPLINARY
THERMAL SCIENCE
LABORATORY**

LOW GRADE WHR TO COOLING - ARPA-E ARID PROJECT

- Utilizing $\sim 100^{\circ}\text{C}$ power plant waste heat to reduce dry-cooling load
- Low cost system, high COP
- Reduction in dry-air heat exchanger size
- $250 \text{ kW}_{\text{th}}$ demonstration early 2017



Bandhauer and Garland, 2016



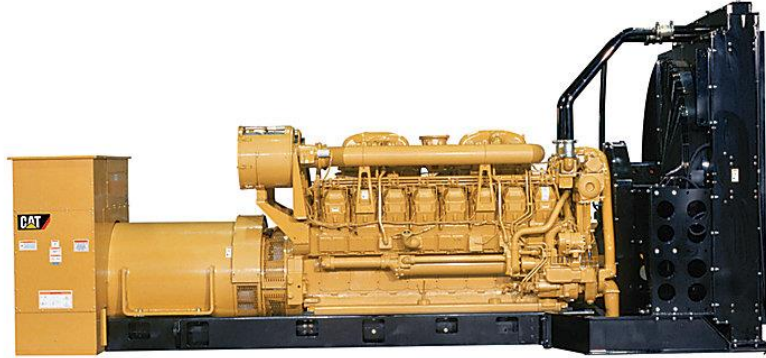
PRESENTATION OUTLINE

- **Fundamental Thermodynamic Considerations**
- **Overview of Mechanical System Technology Options**
- **Challenges for WHR Commercialization**
- **Potential “ARPA-e Hard” Challenges for Mechanical Systems**



CYCLE THERMODYNAMIC CONSIDERATIONS

WASTE HEAT FROM REPRESENTATIVE ENGINES



<http://www.cat.com/>

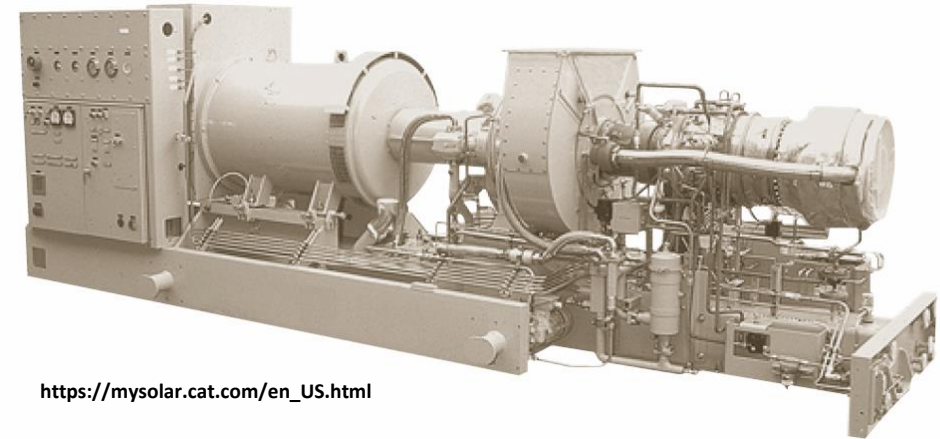
CAT 3516B Engine:

1.6 MW_e

1.6 MW_{th} exhaust

(517°C to 15°C, ~3 kg/s)

1.2 MW_{th} coolant/other



https://mysolar.cat.com/en_US.html

Saturn 20PG Gas Turbine:

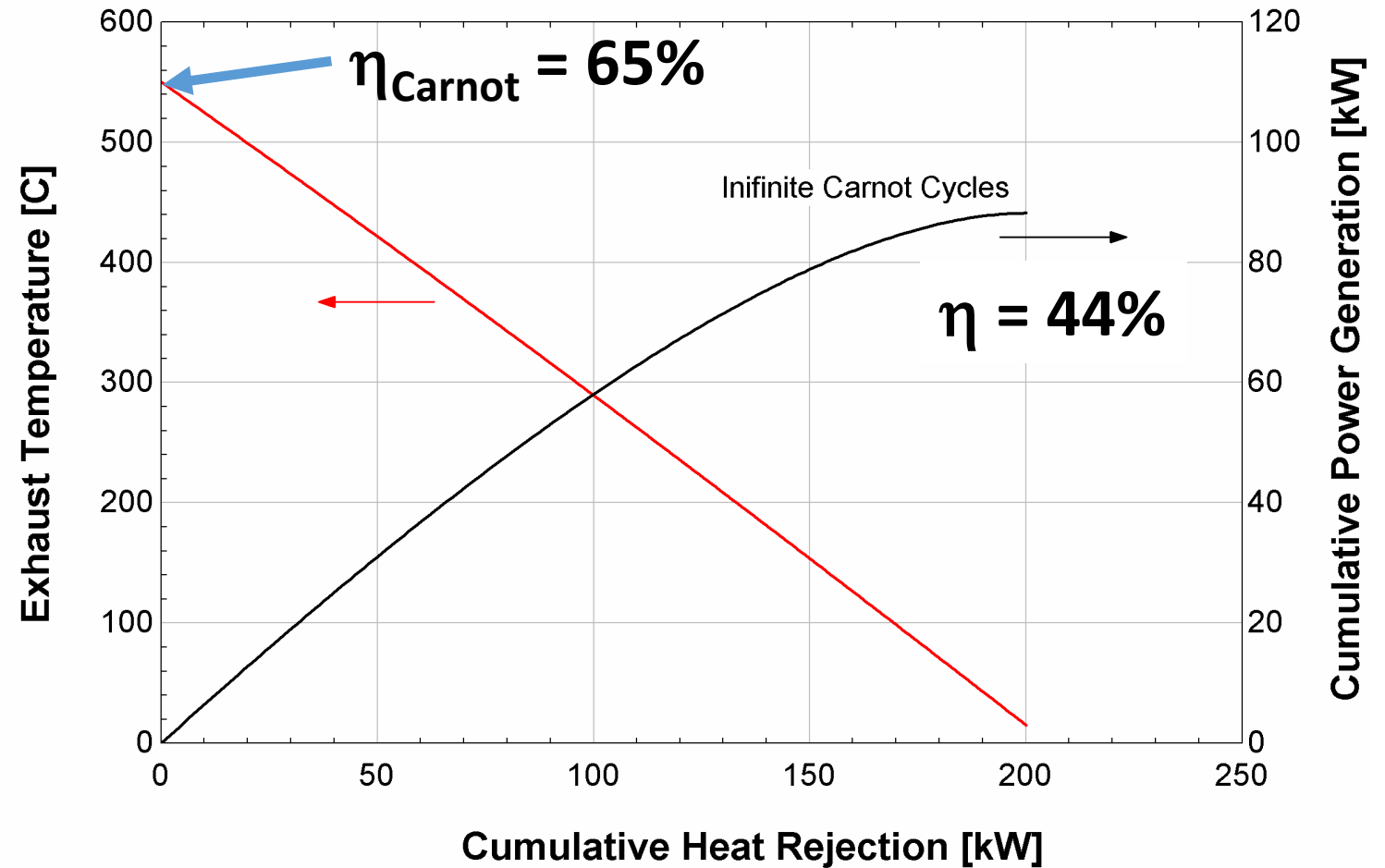
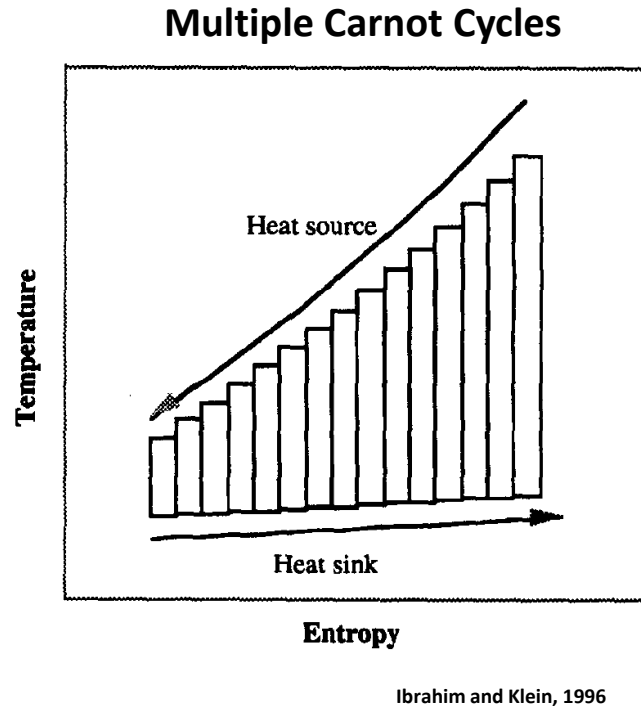
1.2 MW_e

3.3 kW_{th} exhaust

(504°C to 15°C, 6.5 kg/s)

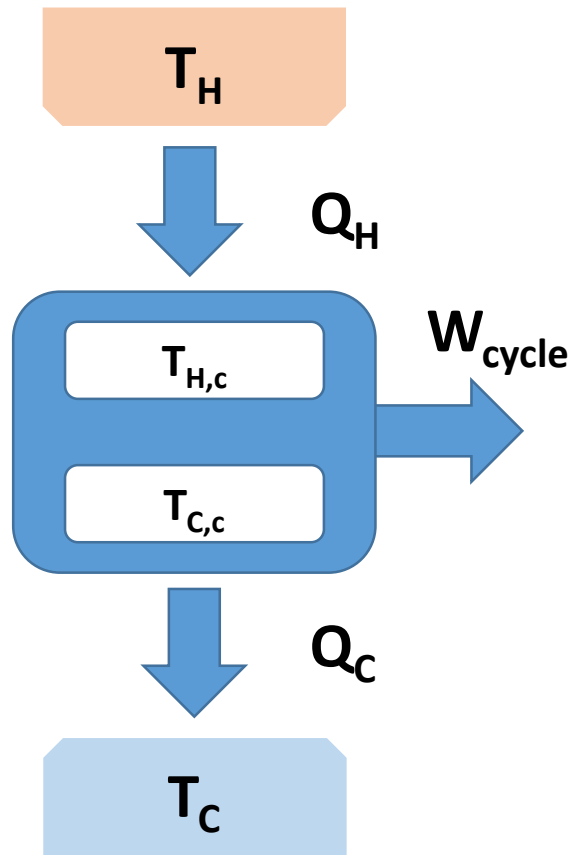
*Higher temperature heat in exhaust gases,
must be cooled to extract heat*

DIESEL EXHAUST WASTE HEAT ANALYSIS



As heat is removed, “reservoir” temperature is reduced – even infinite reversible engines below inlet Carnot limit

FINITE DEVICES: HEAT EXCHANGERS



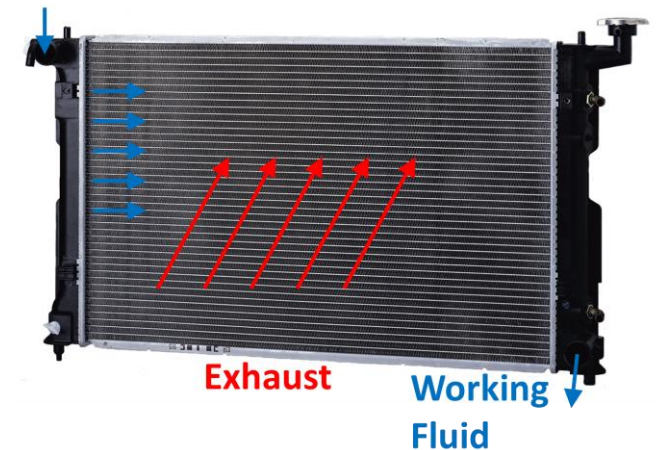
$$Q_H = \varepsilon (\dot{m} C_p)_{\min} (T_H - T_{H,c})$$

$$\varepsilon = 1 - \exp \left[\frac{UA}{(\dot{m} C_p)_{\min}} \right]$$

$$UA = \left[\frac{1}{(hA)_H} + R_{\text{wall}} + \frac{1}{(hA)_{H,c}} \right]^{-1}$$

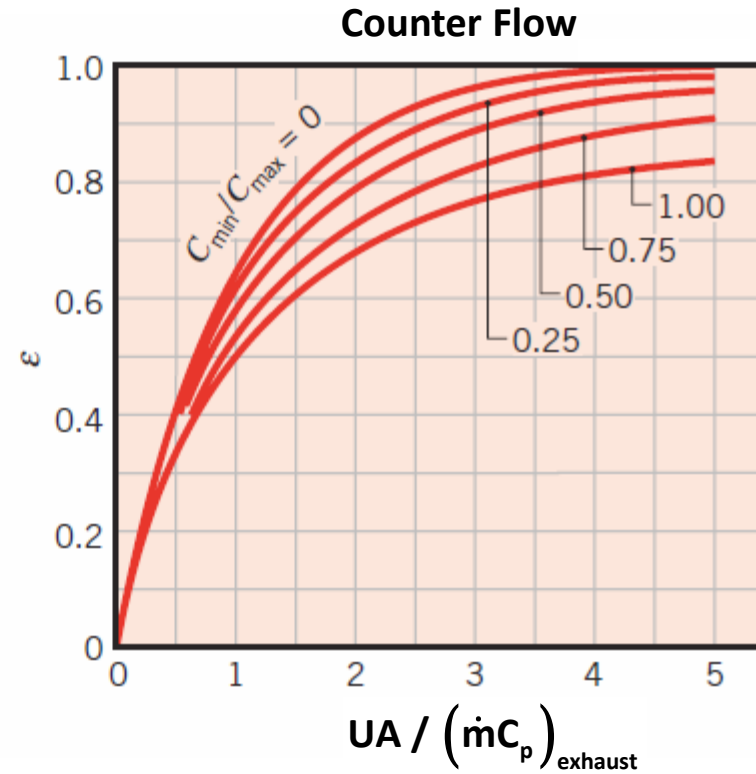
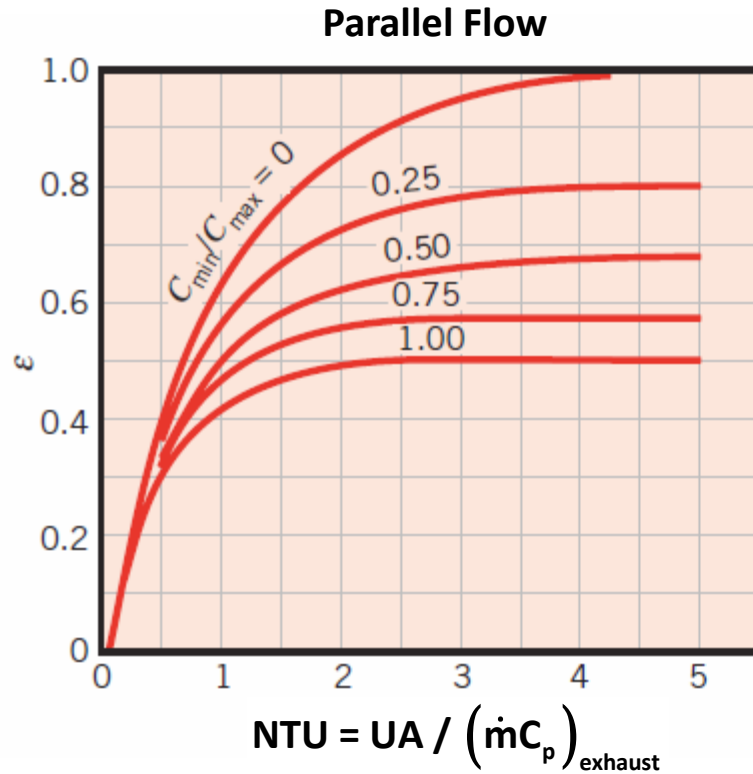
Process	h (W/m ² · K)
Free convection	
Gases	2–25
Liquids	50–1000
Forced convection	
Gases	25–250
Liquids	100–20,000
Convection with phase change	
Boiling or condensation	2500–100,000

Incropera and Dewitt, 1996



*Exhaust gases: large A required for cycle “reservoir”
to approach waste heat temperature*

HEAT EXCHANGER EFFECTIVENESS



Incropera and Dewitt, 1996

- NTU increases, effectiveness increases
- Larger UA: more heat transfer, but diminishing rate of return

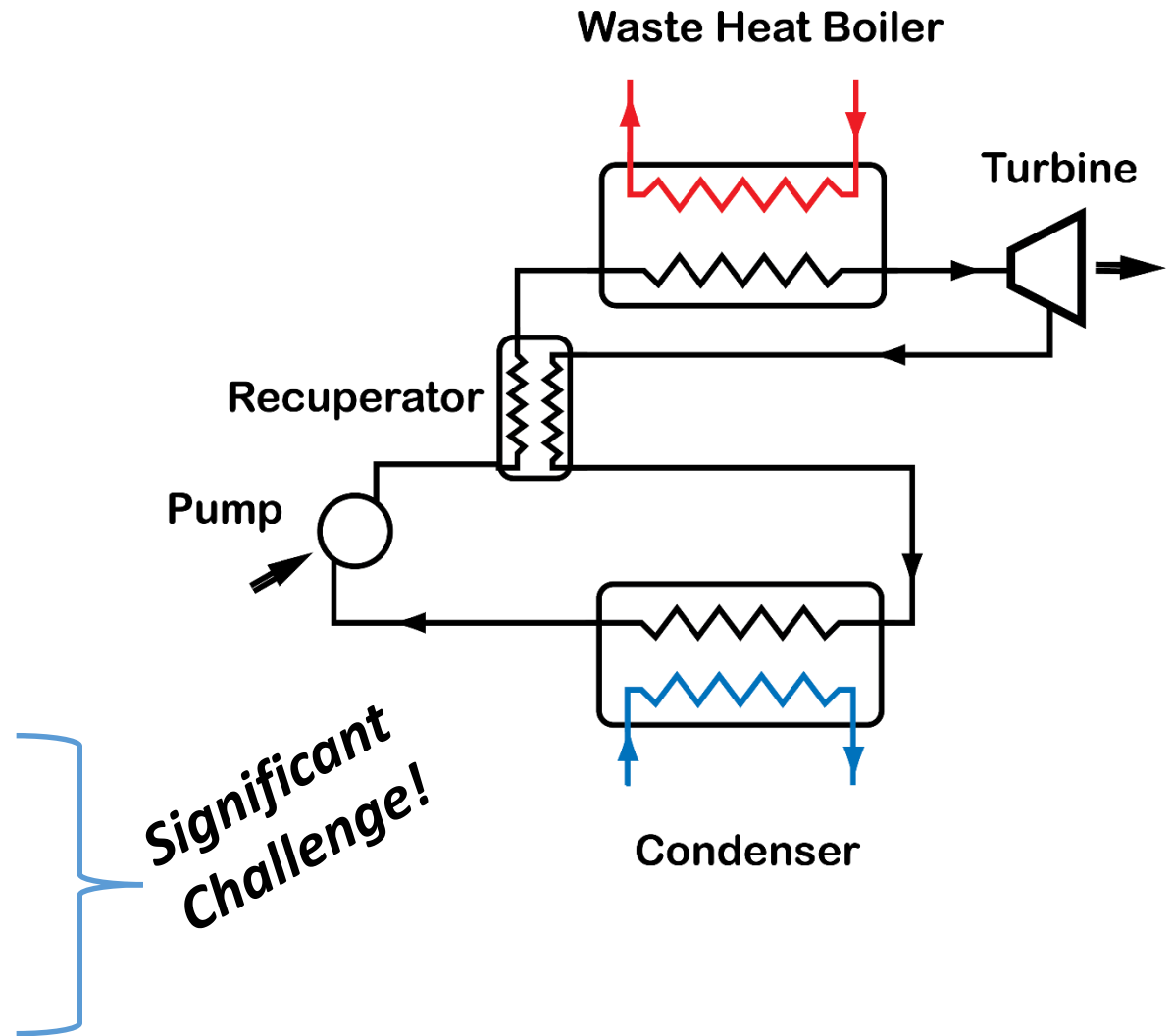
Extracting more heat can cost \$\$\$



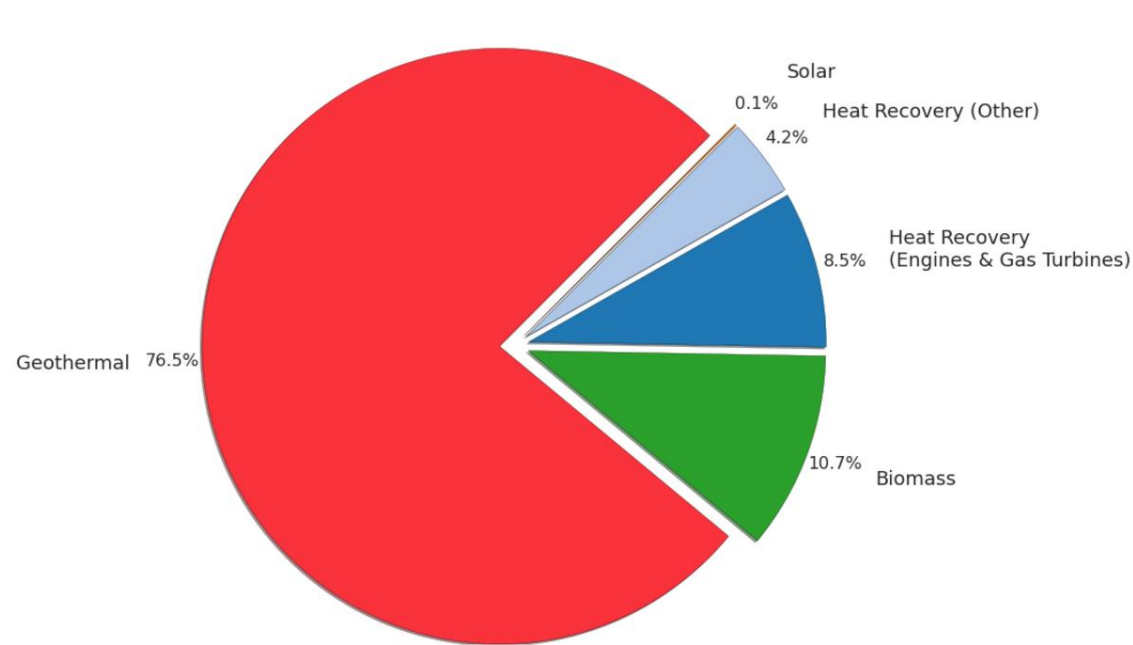
OVERVIEW OF MECHANICAL WHR SYSTEMS

ORGANIC RANKINE CYCLE

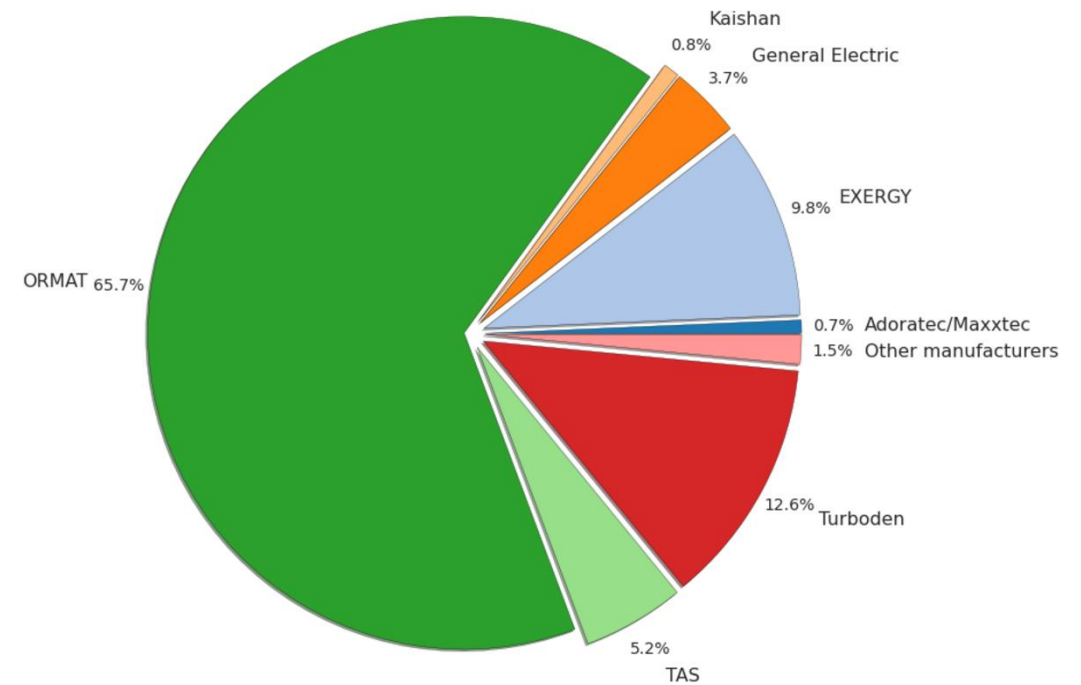
- Largest and most mature technology
- Similar to steam cycle, but (typically) with carbon containing fluid
- Examples: n-pentane, R245fa, ethanol, others (siloxanes)
 - Low flammability fluids tend to decompose at low temperatures
 - High flammability fluids tend to survive higher temperatures



ORC INSTALLS ACROSS THE WORLD



Installed capacity - Market share - Last update : January 21th, 2016



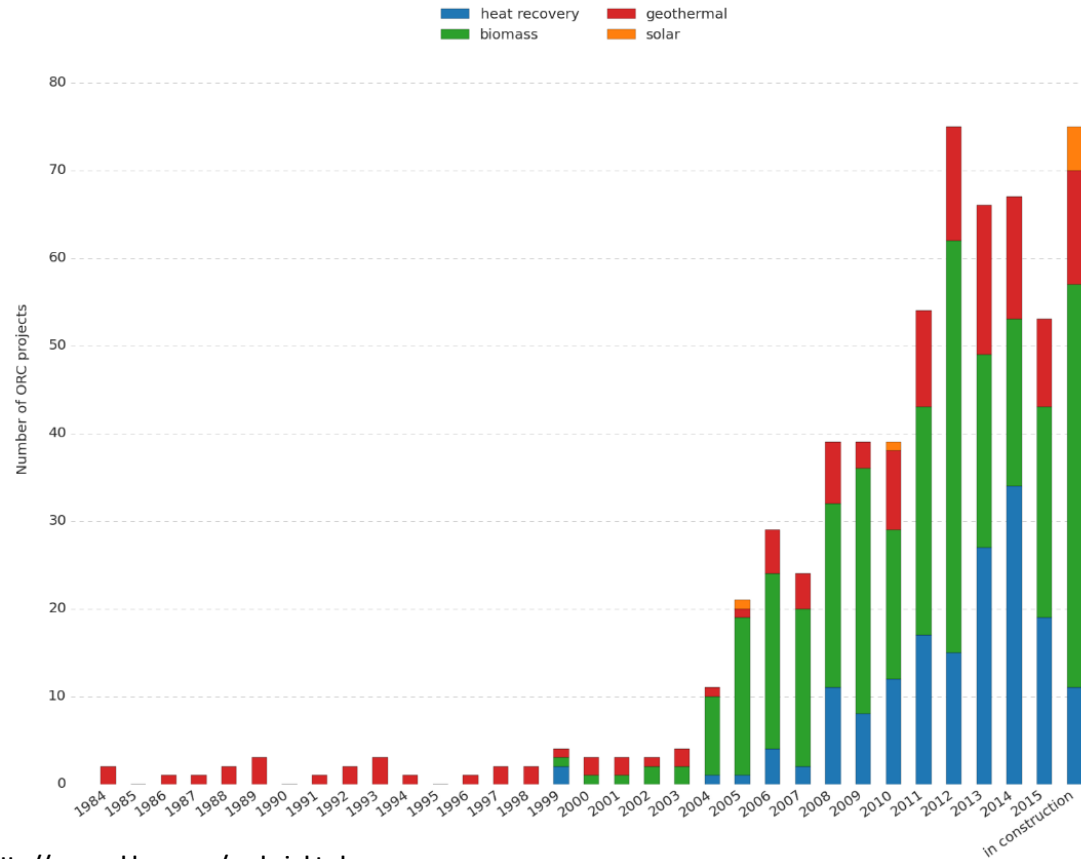
Installed capacity - Market share - Last update : January 21th, 2016

<http://orc-world-map.org/analysis.html>

Majority of installed capacity >50 kW are geothermal installations

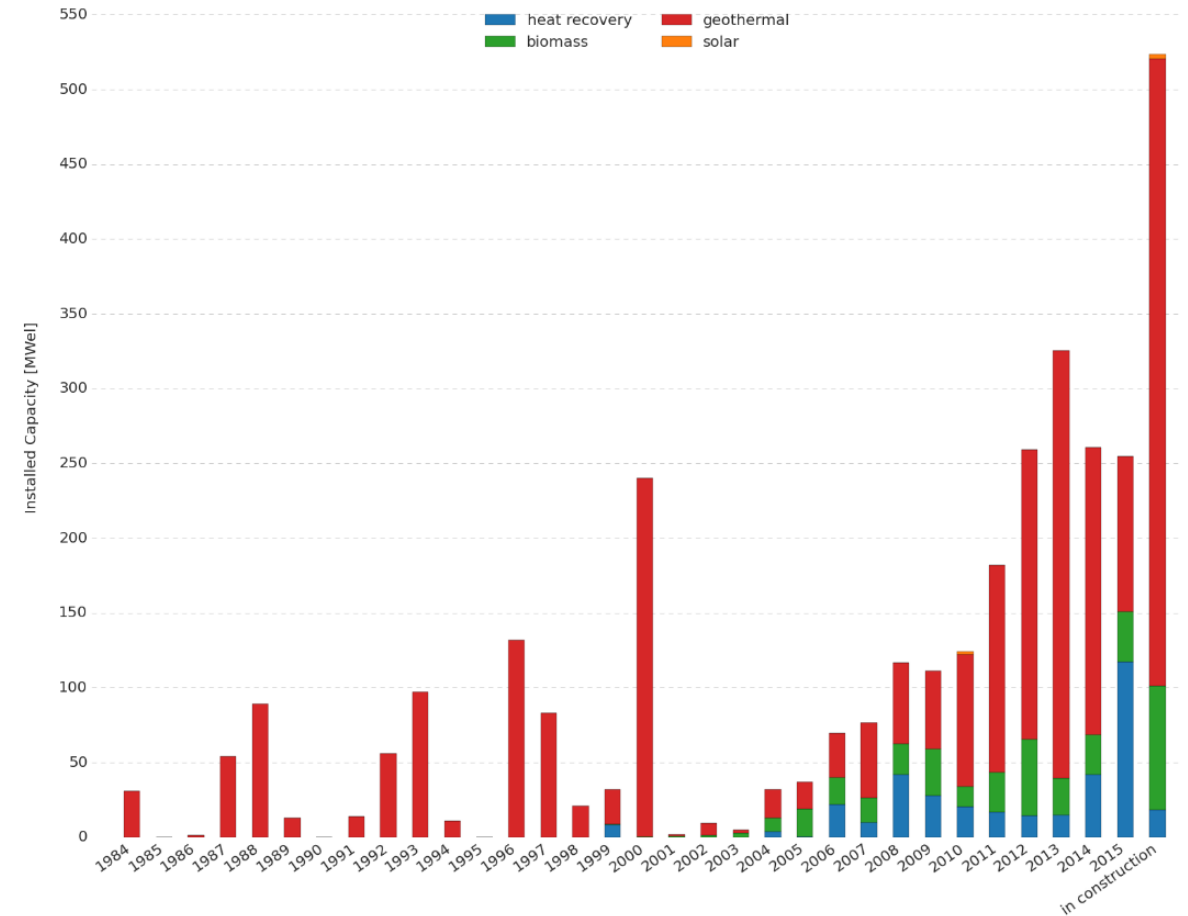
GROWTH IN ORC MARKETS

Installed projects, per year and per application



<http://orc-world-map.org/analysis.html>

Installed capacity, per year and per application



Large number of biomass and heat recovery installations in last decade, geothermal capacity still dominates

DOE SUPERTRUCK EFFORT

- U.S. Department of Energy SuperTruck program
 - Goal: Raise engine efficiency to 55%
 - WHR used by majority of participants

Strategy	Cummins	Daimler	Navistar	Volvo
Engine downsizing	No	Yes	No	Yes
Engine downspeeding	Yes	Yes	No	Yes
Transmission	Automated manual	Automated manual	Dual-mode hybrid	Dual-clutch automated manual
Hybridization*	No	Mild	Full (series/parallel)	No
Organic Rankine cycle	Yes (mechanical)	Yes (electric)	No	Yes
Turbocompounding	No	No	Yes (electric)	Yes (mechanical)

Delgado and Lutsey, 2014

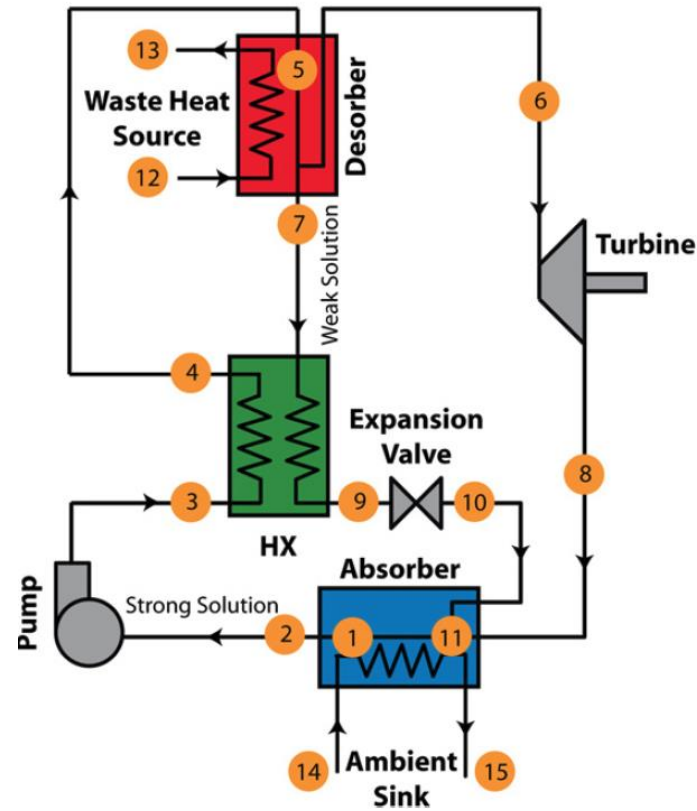
3.6 BTE % pt.
improvement



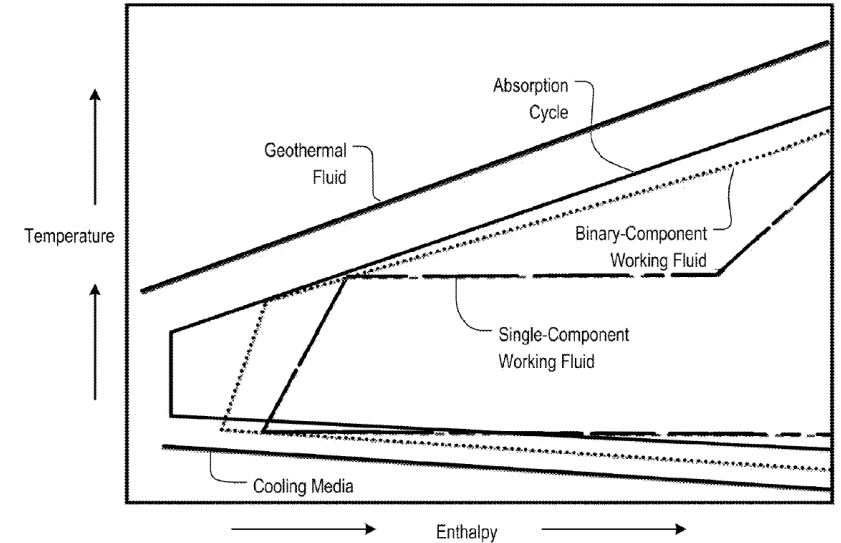
<http://social.cummins.com/>

MALONEY-ROBERTSON/KALINA CYCLE

- Maloney and Robertson (1953) investigated absorption power cycle, similar performance to ORC
- Kalina (1983) proposed similar cycle, adjusted concentration in ammonia-water system to match temperature glide of exhaust stream
- System efficiency higher, cost likely higher than ORC



Little and Garimella, 2011



Nagurny et al., 2013

KALINA CYCLE CASE STUDIES

DOE Program

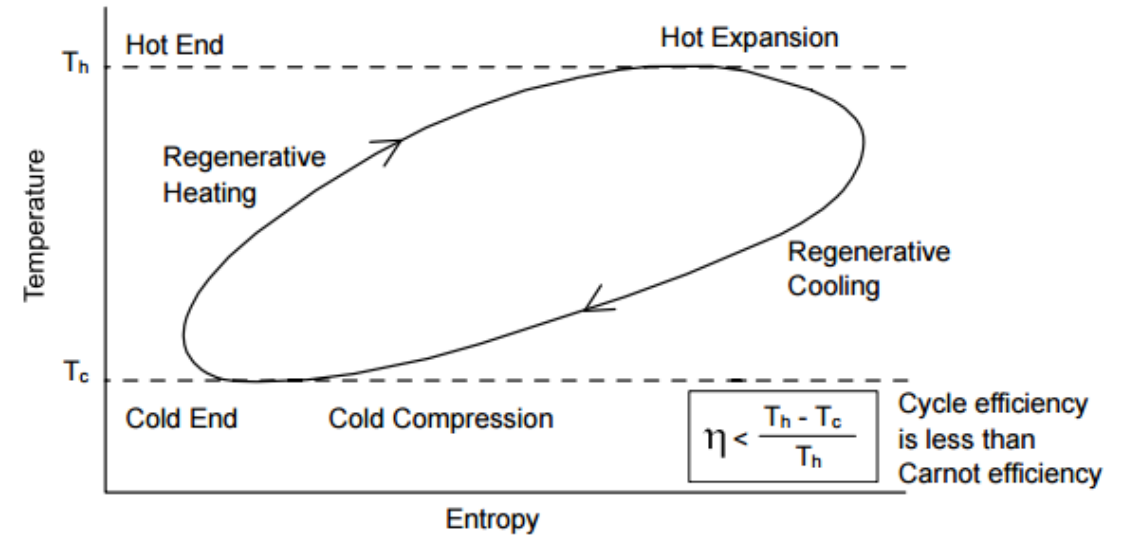


Name	Country	Commissioned	Output (MW)	Heat source
Canoga Park	USA	1992	6.5	Nuclear waste heat
Fukuoka	Japan	1998	4	Waste incineration
Sumitomo Metals	Japan	1999	3.5	Waste heat
Husavik	Iceland	2000	2	Geothermal
Fuji Oil	Japan	2005	3.9	Waste heat
Bruschal	Germany	2009	0.6	Geothermal
Unterhaching	Germany	2009	3.5	Geothermal
Shanghai Expo	China	2010	0.05	Solar hot water
Quingshui	Taiwan	2011	0.05	Geothermal

<http://www.globalcement.com/>

STIRLING (AND ERICSSON) CYCLES

- Many years of development (DOE solar since 1980)
- Some early stage commercial develop ongoing for both cycles (including for ARPA-e GENSETS program – High T)
- Compact systems at high efficiency at low grade waste heat a challenge due to gas recuperation
- Costs, volume likely higher for low grade waste heat



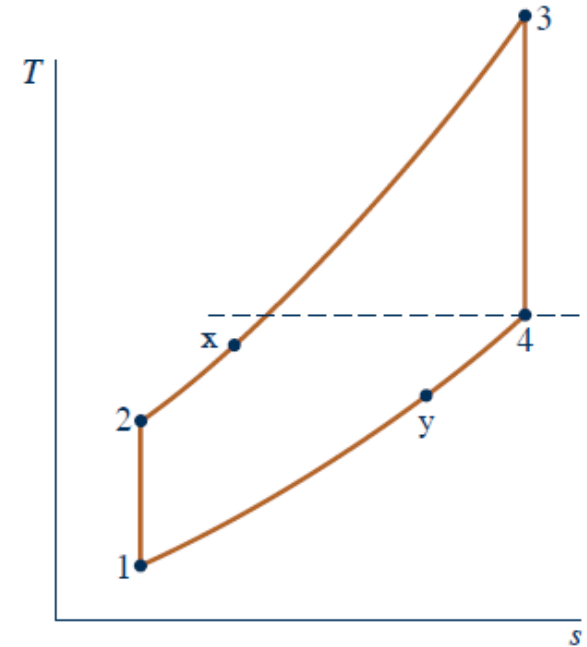
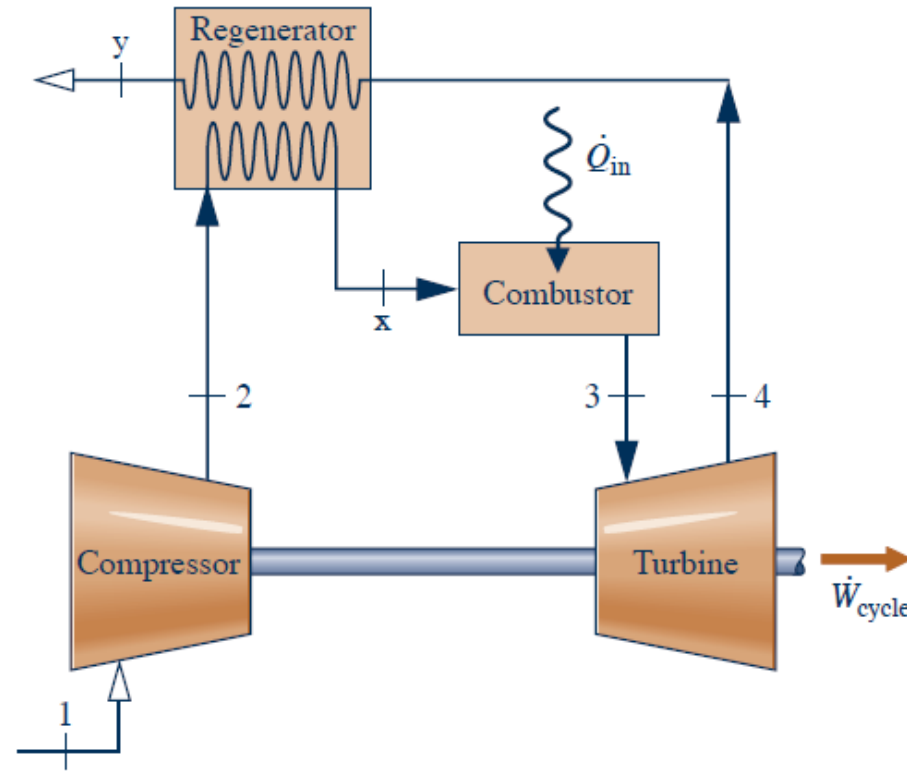
EPRI, 2002

	Manufacturer	Model	P_e (kW)	P_t (kW)	P_f (kW)	η_e
ICE	HONDA	Ecowill	1.0	3.3	5.0	0.200
ICE	AISIN SEIKI	GECC46A2	4.6	10.55	18.0	0.255
ICE	Senertec (DACHS)	HKA G 5.0	5.0	12.12	19.2	0.260
MGT	MTT	Prototype	3.0	15.0	18.75	0.160
mRC	Energetix	Genlec	1.0	8.0	10.0	0.100
mRC	OTAG	Lion	2.0	16.0	19.1	0.104
mRC	COGEN Microsystems	Prototype	2.5	11.0	13.5	0.185
Stirling	MICROGEN		1.0	6.0	7.4	0.135
Stirling	INFINIA		1.0	6.4	8.0	0.125
Stirling	Stirling Systems	SOLO161	2.0	8.0	10.0	0.200
Stirling	SUNMACHINE		3.0	10.5	14.9	0.201
Stirling	DISENCO		3.0	12.0	16.3	0.184
TPV	JX Crystal	Prototype	1.5	9.4	12.2	0.123

Barbieri et al., 2012

BRAYTON CYCLE

- Not typically used for low grade waste heat
- High grade waste heat projects for ARPA-e GENSETS
- DOE investing a significant amount for large scale (10 MW) sCO₂ systems
- Likely to suffer same limitations as Stirling due to large HEX volumes for gas recuperators

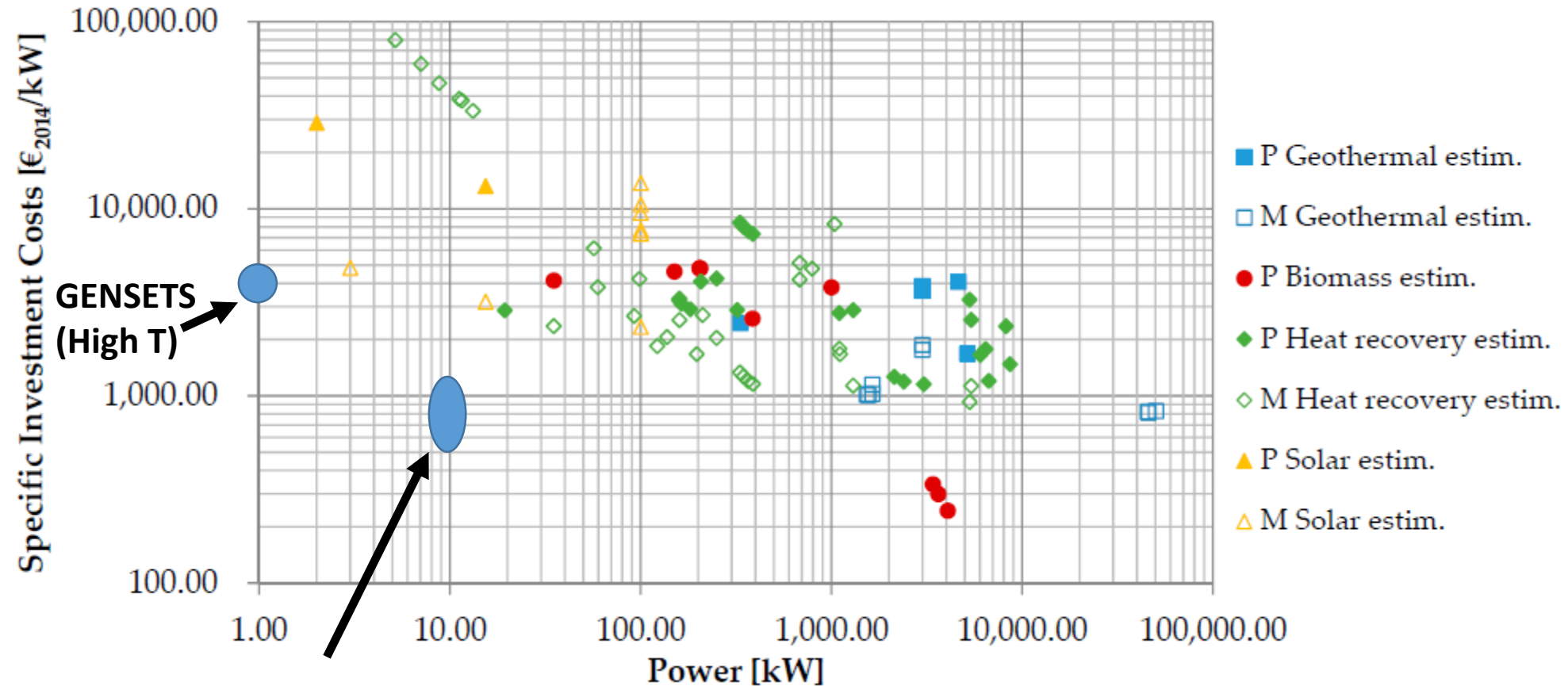


Moran and Shapiro, 2000



MECHANICAL SYSTEM CHALLENGES

ORC SYSTEM COSTS



Lemmens, 2016

Low Grade WHR Target?


Size and Weight Targets Needed

(Need η and Temperature Target Too – perhaps sliding scale?)

HEAT EXCHANGER COST AND VOLUME LIMITATIONS


- Cost of heat exchangers can be >50% of overall system
- Substantial reductions needed to achieve lower overall system cost
- Example: Electratherm 35 kW unit

4200 Stand Alone Specifications



- Dimensions: 2.4 x 2.0 x 2.3 m
- Weight: 3,195 kg / 7,044 lbs
- Customizable balance of plant
- Indoor or outdoor installation
- Manufacturer's Suggested Retail Price: \$173,587

4200-FL Specifications



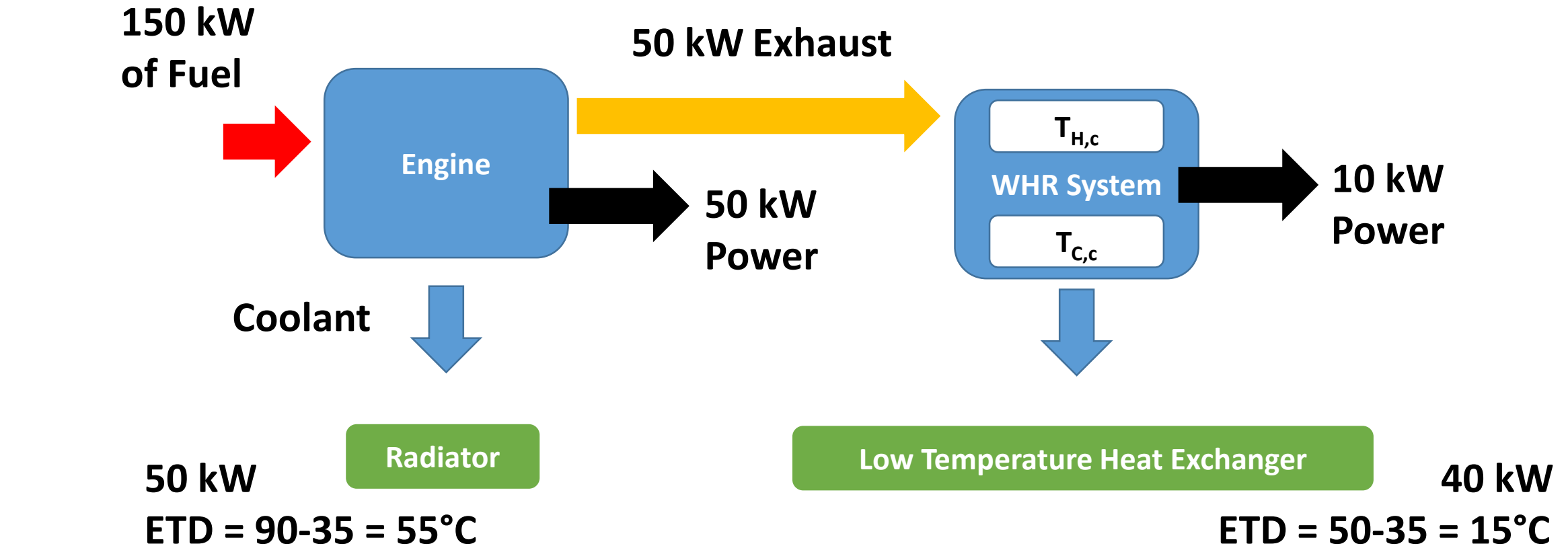
- Dimensions: 12 x 2.4 x 2.9 m
- Weight: 6,095 kg / 13,438 lbs
- Turnkey inc. liquid loop radiator, working fluid, start up and commissioning, hot water bypass (if required)
- Manufacturer's Suggested Retail Price: \$251,935

Renderings may not be exact representations of final Power+ product.

<http://electratherm.com/>

- Differential cost for air cooled unit: \$2200/kWe (not all HX, probable volume discount, but still significant)

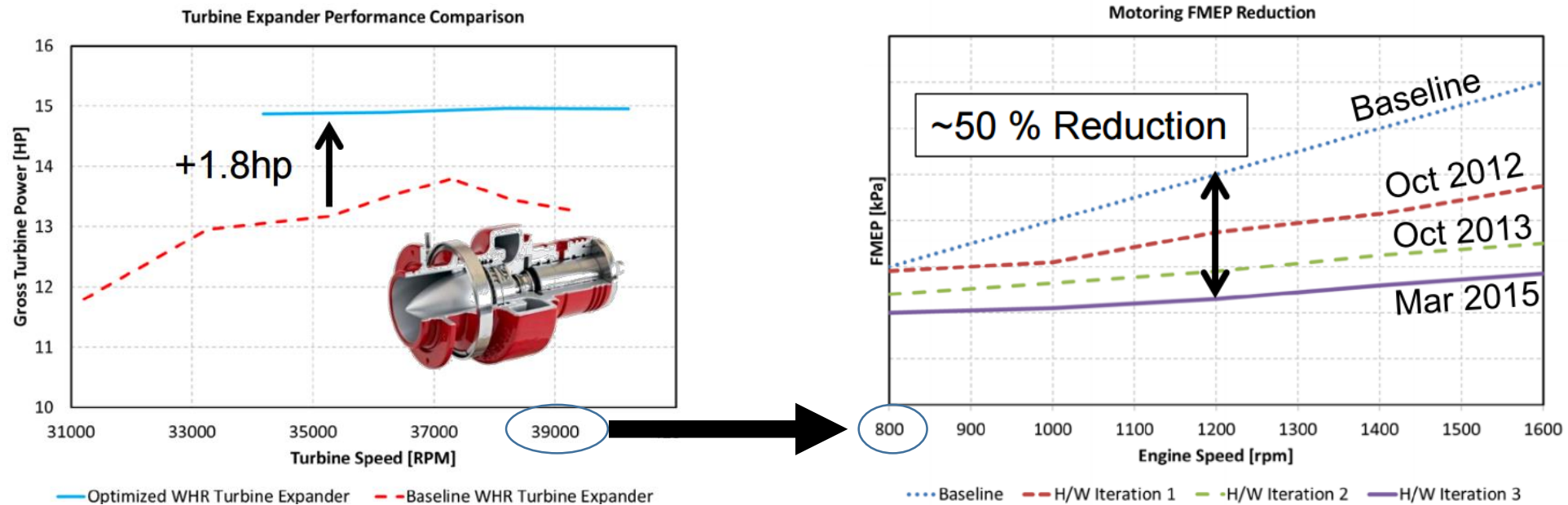
VOLUME: HEAT EXCHANGER SIZE FOR TRANSPORTATION



$$Q_c = \epsilon (\dot{m} C_p)_{\min} (T_{C,c} - T_c)$$

*Most of Normally Discharge Exhaust Heat
is Rejected in HX $\sim 3\times$ Core Face Area of Radiator*

COMPLEXITY: SPEED SYNCHRONIZATION



Koeberlein, 2015

- High speed, high efficiency turbomachines
- Low speed engines
- Need intermediate device to link performance of two system (battery, transmission, etc.)



SUMMARY AND CONCLUSIONS

SUMMARY AND CONCLUSIONS

- ORCs are well established and mature technology, but cost reduction needed at low power outputs and low waste heat temperatures
- Stirling, Brayton cycles: need to address volume, weight, and efficiency challenges at low temperature
- Cost target $< \$500/\text{kW}$ (or lower), efficiency of $\sim 50\%$ of Carnot at 10 kW might be a good target for low grade waste heat (Need TEA for different markets!)
- Potential “ARPA-e Hard” challenges
 - Extreme cost reduction of heat exchangers
 - Inert (and low cost) working fluids without adverse environmental impact, flammability, or other implementation issues (e.g., freezing)
 - Transportation: improved gas heat exchange per unit volume

REFERENCES

- Bandhauer, T. M., and S. Garland, 2016, "Dry Air Turbo-Compression Cooling," Paper 2016-59152, Proceedings of the ASME 2016 Power and Energy Conference, Charlotte, NC.
- Ibrahim, O. M., and Klein, S. A., 1996, "Absorption power cycles," *Energy*, 21(1), pp. 21-27.
- Moran, M. J., and Shapiro, H. N., 2000, *Fundamentals of engineering thermodynamics*, J. Wiley & Sons, New York
- Incropera, F. P., and DeWitt, D. P., 1996, *Fundamentals of Heat and Mass Transfer*, Wiley, New York.
- Delgado, O., and Lutsey, N., 2014, "White Paper: The U.S. SuperTruck Program," Department of Energy.
- Kadota, M., and Yamamoto, K., 2008, "Advanced Transient Simulation on Hybrid Vehicle Using Rankine Cycle System," *SAE Int. J. Engines*, 1(1), pp. 240-247.
- Briggs, T.E., Wagner, R., Edwards, K.D., Curran, S., and Nafziger, E., 2010, "A Waste Heat Recovery System for Light Duty Diesel Engines," SAE International.
- Quoilin, S., Declaye, S., Tchanche, B. F., and Lemort, V., 2011, "Thermo-economic optimization of waste heat recovery Organic Rankine Cycles," *Appl. Therm. Eng.*, 31(14–15), pp. 2885-2893.
- Little, A. B., and Garimella, S., 2011, "Comparative assessment of alternative cycles for waste heat recovery and upgrade," *Energy*, 36(7), pp. 4492-4504.
- Nagurny, N. J., Jansen, E. C., and Panchal, C. B., 2013, "Working Fluid Power System fo Low-Temperature Rankine Cycle," US 8,578,714 B2.
- *Stirling Engine Assessment*, EPRI, Palo Alto, CA: 2002. 1007317
- Barbieri, E. S., Spina, P. R., and Venturini, M., 2012, "Analysis of innovative micro-CHP systems to meet household energy demands," *Applied Energy*, 97, pp. 723-733.
- Lemmens, S., 2016, "Cost Engineering Techniques and Their Applicability for Cost Estimation of Organic Rankine Cycle Systems," *Energies*, 9(7), p. 485.
- Koeberlein, D, 2015, Cummins SuperTruck Program, DOE Project ID: ACE057.



THANK YOU! QUESTIONS?